

IMPROVEMENTS IN REGENERATIVE FREQUENCY DIVIDERS

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ABSTRACT

This report describes novel regenerative frequency dividers where the use of multiple-tuned circuits in the mixer or multiple-tuned circuits in conjunction with crystal rectifier distorters provide a number of advantageous operating characteristics with a minimum number of tubes. The particular circuits have a high division ratio, require no voltage-regulated power supplies, and exhibit self-starting and locking qualities heretofore not available with regenerative frequency divider techniques.

PROBLEM STATUS

This is an interim report on the problem; work is continuing.

AUTHORIZATION

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NL 490-022

IMPROVEMENTS IN REGENERATIVE FREQUENCY DIVIDERS

INTRODUCTION

The widespread use of secondary frequency standards during the last few decades has always presented the need for a reliable frequency dividing system. In general these standards derive their precise frequency from a precision tuning fork, or, as in the case of the more modern systems, from an oscillator controlled by a piezo-electric crystal operating in a bridge circuit or one referenced to a gas absorption line. Crystal oscillators may operate at any desired frequency, but for higher accuracy they are usually designed to operate in the range from fifty kilocycles to one megacycle per second. A single reference frequency of high precision and stability has, however, only limited use. Thus, it remains to produce numerous other frequencies in harmonic and subharmonic relationships of the same precision as the reference to provide a practical frequency standard. Multiple and submultiple frequencies of the reference are needed as comparison frequencies. Depending upon the particular application, they range from below the crystal frequency up through the microwave region. Techniques for the production of high precision multiple frequencies are quite well known, and this report emphasizes advancements in the less fully described field, that of the production of submultiple frequencies.

If the crystal-controlled reference oscillator is of a design operating at a moderately high frequency, it is possible that a submultiple frequency of the same precision would be needed for comparison with a Bureau of Standards standard frequency transmission. Under other modes of operation, the accuracy is checked by causing the controlled oscillator to drive indirectly a synchronous clock which is rate compared with standard time. This type of operation requires that the precision frequency be divided down to a low frequency possessing the same degree of accuracy as the crystal oscillator. In addition to the above, precise submultiple frequencies are necessary for calibrating measuring equipment whose function is to determine the beat, or difference frequency between the unknown frequency and one of the multiple-frequency check points. This requirement usually calls for several frequencies in the low audio-frequency range, that is, from one-hundred to several thousand cycles per second.

A regenerative frequency divider of improved stability and small physical size was required as one phase of BuAer problem A-262ED-R. For this problem it was necessary to provide standard reference frequencies at 10 kc, 1.0 kc, and 0.1 kc which were to be derived from a crystal oscillator operating at 100 kc. This requirement necessitated the development of a minimum number, preferably three ten-to-one dividers, the first dividing from 100 to 10 kc, the second dividing from 10 to 1.0 kc, and the third dividing from 1.0 to 0.1 kc. It was a further requirement that the resulting divider would be one which: (1) would operate with high stability over a wide range of B supply voltage, (2) would operate with high stability over a wide range of input signal voltage, (3) would have a small physical

size, and (4) would exhibit no tendency to oscillate at a frequency controlled by its own circuit constants in the absence of an intended input signal voltage and yet be self starting.

In a survey of literature on the art, numerous examples of the synchronized self-oscillating frequency dividers were found. Dividers of this type, by their very nature, fail to meet the fourth and very important requirement set down above. Information has been published, on the regenerative frequency divider or quasi-stable oscillator indicating both its theoretical and practical desirability, (see references 1, 2, and 3 detailed later). However, even the most advanced designs appear to possess limitations of simplicity and reliability such as uncertain starting characteristics or operation over only a restricted plate supply range, etc.

Since the problem necessitated three dividers having characteristics not available in prior art, it was decided to initiate circuit research toward a simplified regenerative divider with improved self-starting characteristics, greater plate and input voltage operating range, and of small physical size.

FUNDAMENTAL CONSIDERATIONS OF A QUASI-STABLE OSCILLATOR

A search of the literature showed some few references to a type of regenerative divider referred to as "quasi-stable frequency divider." The first of these circuits were apparently due to Sterky¹ and Longo.² Fortescue³ has shown that the quasi-stable frequency divider is in reality a special case of the synchronized oscillator. A review of Fortescue's analysis is of assistance in understanding the development of the subject frequency dividers. Reference is made to the simplified oscillator circuit shown in Figure 1. In this circuit the transformer is assumed to have 1:1 ratio, no leakage, and the tube is a pentode having plate current approximately independent of plate voltage swing. The effect of harmonics in the grid-voltage waveform on the energy feedback to the oscillating circuit LC will be considered, and it will be shown that the amplitude and phase of the feedback term depends upon the amplitude and phase of the harmonics. Consider the grid-voltage waveform to be

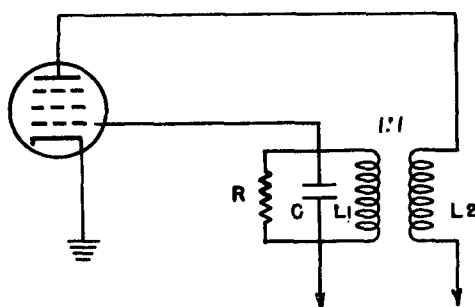


Figure 1 - Simplified oscillator circuit

$$V_g = \sin \omega t + k_n \sin (n\omega t + \phi_n)$$

when only one harmonic is taken.

With the plate current written as

$$i_p = a v_g + b v_g^2 + c v_g^3 + \dots$$

Substitution of the previous expression for V_g

¹ Sterky, H., "Frequency Multiplication and Division," *Proc. I.R.E.* 25, 1153-1173, September 1937

² Longo, G., "Multiplication of a Frequency by Simple Fractional Numbers," *L'Onde Electrique* 13, 97-100, February 1934.

³ Fortescue, R. L., "Quasi-Stable Frequency-Dividing Circuits," *J. Inst. Elec. Engrs.* (London) 84:693-8, June 1939

produces a Fourier series for i_p . The fundamental term of this series will consist of $av \sin \omega t$ plus a component from such products as

$$(v^{n-1} \sin^{n-1} \omega t) [vk_n \sin(n\omega t + \phi_n)].$$

It can be seen that harmonics can intermodulate between themselves and with the fundamental, and the general effect is expressed by writing the fundamental term of the plate current as

$$I_0 = av \sin \omega t + f_1(v, a, b, \dots k_n \dots \phi_n, \text{ etc.}) \sin \omega t + f_2(v, a, b, \dots k_n \dots \phi_n, \text{ etc.}) \cos \omega t.$$

The first term is the "linear" term used in simplified oscillator theory and the other terms are the so-called intermodulation terms. It is clear that magnitude and phase of the feedback voltage are in part due to harmonics in the grid circuit. In Figure 1, when the state of steady oscillation is reached, the grid voltage must be equal to the product of the LRC circuit impedance and the plate current. Thus, one may write

$$v \sin \omega t = Z(av \sin \omega t + f_1 \sin \omega t + f_2 \cos \omega t)$$

where f_1 and f_2 are the amplitudes of the intermodulation terms depending upon the harmonics. For this identity to be true, the frequency must be such that LRC circuit has a phase angle given by $\arctan(-f_2)/(av + f_1)$. This is, in general, not zero and the frequency of oscillation is not that at which the circuit is resistive, $1/(2\pi\sqrt{LC})$, as given by linear analysis.

So far no mention has been made of the source harmonic in the grid voltage. If one makes use of this parameter and injects a near multiple of the "free" oscillation frequency, one can exercise considerable control over the frequency of oscillation. As an example, an oscillator that has a frequency of 1000 cps when 3000 cps is injected in series with the grid, may have a frequency of 1200 cps when the 3000 cps is removed, while its oscillation frequency calculated by linear analysis would be $1/(2\pi\sqrt{LC}) = 1300$ cps. It is the steady oscillation at an exact submultiple of an injected frequency that permits the construction of a desirable type of frequency divider. The effect is due directly to the non-linear action of the tube and the injected harmonic, and the greater the ratio of the "intermodulation" feedback to the "direct" feedback the more the injected harmonic can control the oscillation.

The synchronizing action is not fundamentally due to the presence of the "direct" feedback and if the "direct" feedback is decreased while the "intermodulation" feedback is increased the total feedback can still be sufficient to maintain oscillation. When this process of decreasing "direct" feedback while increasing intermodulation feedback is carried far enough, the action becomes insufficient to maintain oscillation in the absence of an injected harmonic and quasi-stable system is obtained. This is recognized as a system meeting the requirement of no output in the absence of an input harmonic, and it is a cardinal theoretical characteristic of this type of divider that it is totally incapable of oscillation in the absence of an input (injected) multiple frequency. In the presence of an intended input signal, it does oscillate, or to use the preferred terminology, regenerates and produces an output frequency which is an exact submultiple of the input signal.

While the concept of the so-called quasi-stable oscillator is helpful in determining the requirements for the desired frequency dividers, the authors have purposely omitted the use of this description and refer to the dividers resulting from this development as regenerative frequency dividers, to avoid confusion in the minds of readers and future users.

Several circuits based upon the principles described above are found in the literature. One class described by Sterkly and Longo makes use of a balanced modulator, while another type uses frequency discriminatory tuned circuits in conjunction with pentode amplifiers to accomplish the required increase in the ratios of intermodulation feedback to direct feedback. By far the largest number of these circuits divide by low ratios, usually by two or three, but some few are reported to divide by ratios as high as 1 to 6. It is pointed out by the literature that higher ratios are apparently possible, but without fail, as the division ratio increases, the problem of making the divider self-starting increases. In the end, the previously mentioned starting problem and the associated problems of operating stability have, heretofore, meant failure to provide satisfactory operation at high dividing ratios.

CONSIDERATIONS TOWARD IMPROVEMENT OF THE REGENERATIVE FREQUENCY DIVIDER

At the beginning of this development, the most advanced circuit apparent in the literature, as described by Stansel,⁴ made use of a pentagrid converter tube for production of harmonics in a manner indicated in Figure 2. One problem thus appeared to be that of increasing the desired harmonics feedback, while at the same time suppressing the direct feedback, to the point that 1:10 division ratio and self-starting high stability of operation would be possible. To accomplish this, the operating points of the tubes were set to cause as much harmonic production as possible. In addition it was recognized that high Q tuned circuits would be important in diminishing the direct feedback while serving to obtain high gain for the intermodulation feedback. As an additional means of producing sufficient intermodulation feedback, a second circuit tuned to $3f/n$, where f is equal to the input frequency and n equal to the total division ratio, was placed in the plate circuit of the first tube, Figure 3, thus allowing it to produce an appreciable voltage of frequency, $3f/n$, as well as frequency f/n . The following pentode was thus allowed to multiply simultaneously by 3 and 9 to produce an increased voltage of $(n-1)f/n$ as the intermodulation feedback.

For a more complete discussion of the operation of a frequency divider embodying the pregoing improvements, refer to Figure 3. With the divider assumed to be in operation, a signal of frequency f appears on the number 3 grid of tube V_1 (6SA7). A signal, whose origin will be apparent momentarily, is assumed at grid number one of tube V_1 . Due to the non-linear action of this tube, intermodulation or mixing takes place, and the f/n and $3f/n$ components of the plate current are selected by the tuned circuits L_1C_1 and L_2C_2 , tuned to these frequencies. The f/n and $3f/n$ voltage is supplied to the grid of tube V_2 (6SJ7) which multiplies simultaneously by three and nine. The output circuit L_3C_3 of V_2 is tuned to $9f/n$. It selects this component of the V_2 plate current and it is this voltage that is applied to the number one grid of tube V_1 . Thus the circuit Figure 3 operates in a manner analogous to that of Figure 1 where the f/n voltage is suppressed and the $9f/n$ voltage is augmented to produce the intermodulation feedback. In the case of this circuit, Figure 3, stray feedback of the f/n voltage is kept at a low value and the total amount that reaches the grid circuit of tube V_1 is sufficiently low to cause the circuit to be incapable of output without the injection of the f voltage and the resultant production of the $9f/n$ voltage.

A discussion of the self-starting action of this circuit is somewhat complicated, though it is essentially the same as the starting action of a conventional oscillator. Intermodulation

⁴ Stansel, F. R., "A Secondary Frequency Standard Using Regenerative Frequency-Dividing Circuits," *Proc. I.R.E.* 30, 157-162, April 1942

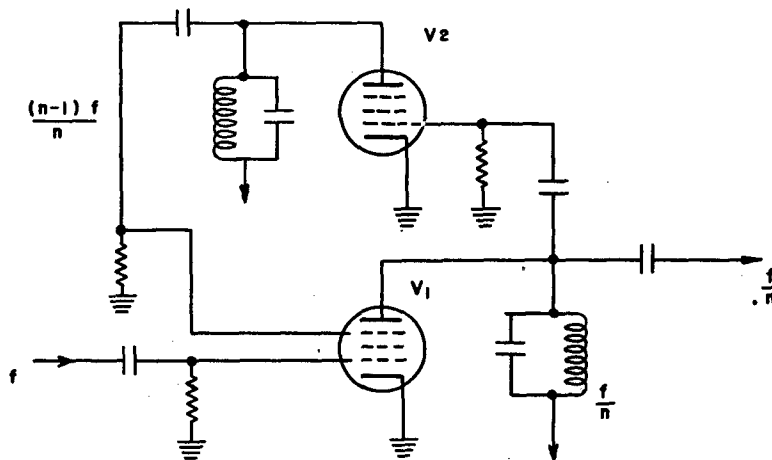


Figure 2 - Simplified divider circuit

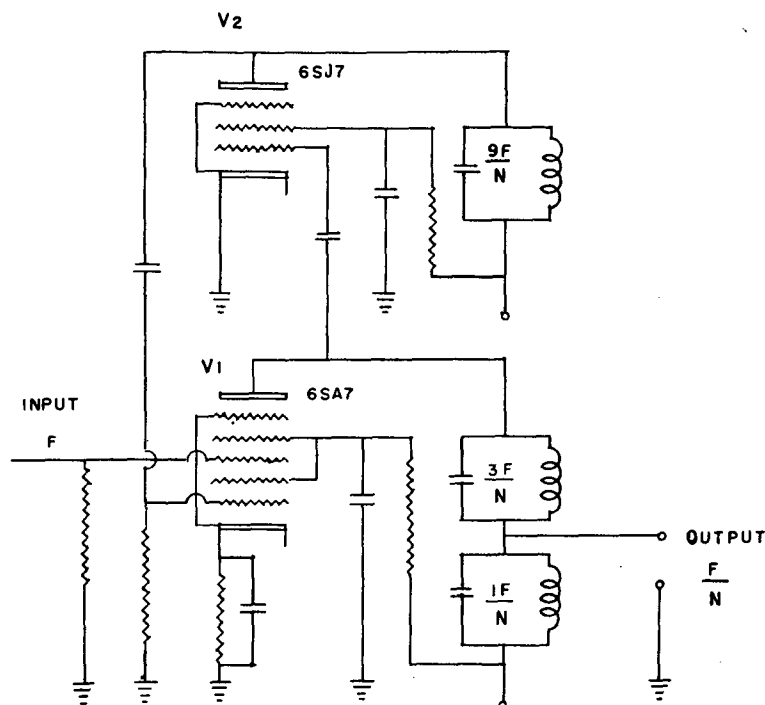


Figure 3 - Divider circuit with additional tuned circuit

takes place between the injected f and $9f/n$ components of circuit noise or possibly the $9f/n$ components of some transient caused by the closing of a switch or the initial adjustment of the various voltages. If the gain condition for the $9f/n$ voltage is sufficient, the dividing action will start and build up to steady state, with the divided output obtainable across the f/n tuned circuit.

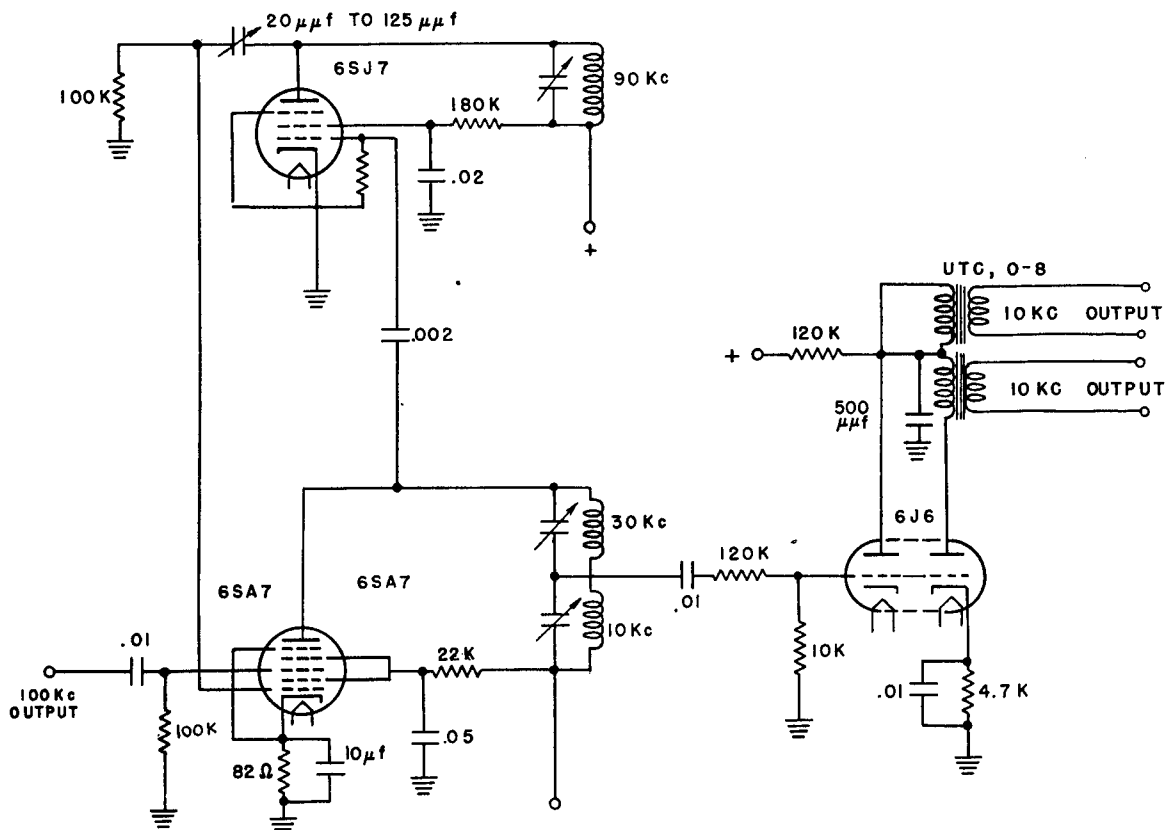


Figure 4 - Regenerative frequency divider of the first type

TYPICAL DIVIDERS

Two types of frequency dividers were developed embodying the principles previously set forth. One type employs multiple-tuned circuits as described by Figure 3; the other, in addition to the tuned circuits, employs crystal rectifiers to further augment harmonic distortion.

Figure 4 shows the circuit diagram of a 100 kc to 10 kc frequency divider of the first type. This figure is more complete than Figure 3 inasmuch as it shows, in addition, one type of suitable output circuit.

Figure 5 shows a frequency divider employing the circuit principles set forth by Figure 3 together with crystal rectifiers to foster the production of harmonics. A cathode follower type output circuit is shown, but this type of output circuit is not restricted to the divider employing both multiple-tuned circuits and rectifier distorters. The addition of the voltage regulator tube, VR105, while not necessary, stabilizes the screen voltage of the mixer tube and the harmonic generator tube, thus allowing the dividing operation to start at the same low input signal voltage for which the dividing operation stops when the input signal is decreased. The result is a slightly better operating characteristic shown later in Figure 7. Because of the increased harmonic production of the circuit, Figure 5, this divider was noticeably easier to adjust for proper operation. The divider shown in Figure 4 required considerable care, in adjusting the feedback voltage so that the fundamental

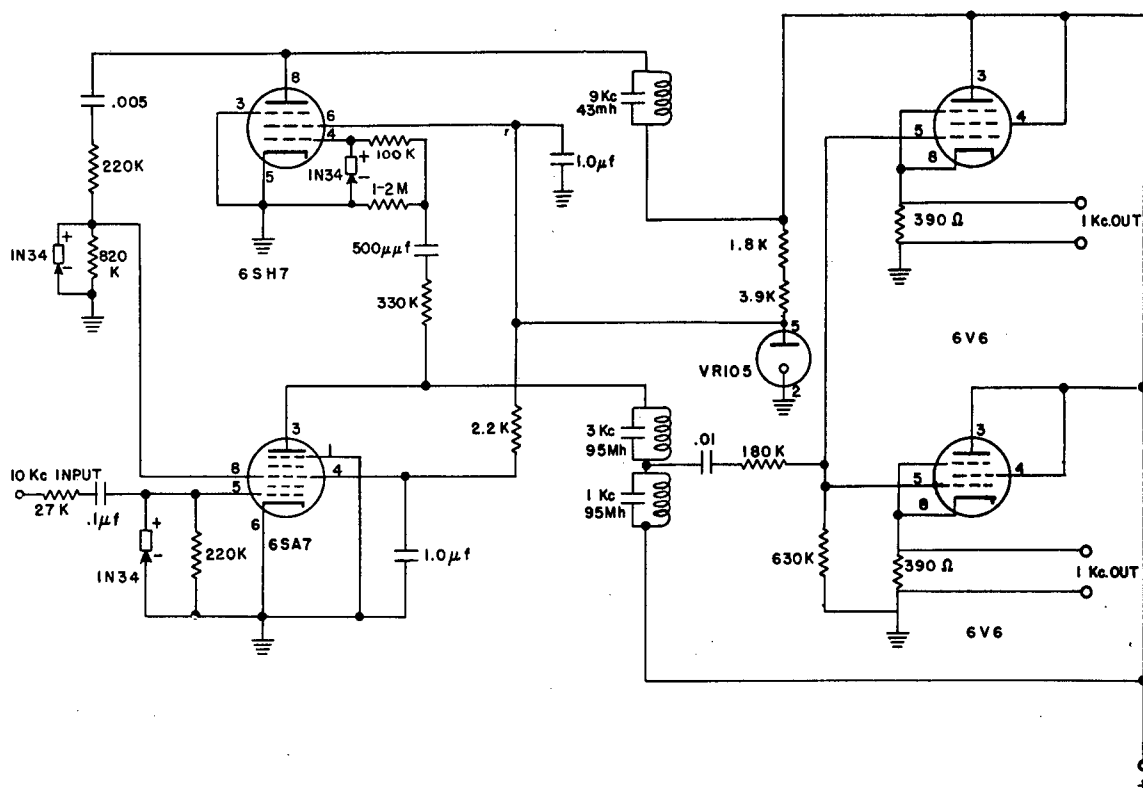


Figure 5 - Regenerative frequency divider of the second type

feedback remained below the critical value while the desired harmonic feedback remained above the value required for satisfactory operation. The range of operation of the circuit shown by Figure 4 is presented by Figure 6. The latter figure shows that this circuit meets the specification of wide range of plate voltage operation and to a reasonable degree the specification of wide range of input voltage operation.

The performance of the circuit, Figure 5, displays a marked improvement in operating characteristics over the circuit of Figure 4 as shown in Figures 7 and 8. The improvement in operating characteristics is undoubtedly due to the addition of crystal rectifier distorters.

It is noted that Figure 4 shows components for the 100 kc to 10 kc range divider, whereas Figure 5 recites the necessary components for the 10 kc to 1.0 kc divider. The display of these two division ranges is not peculiar to the circuits themselves but represents diversification in the employment of the principles employed.

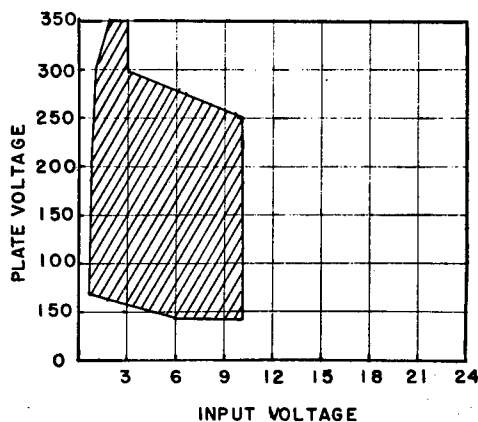


Figure 6 - Operating characteristics of the first type divider

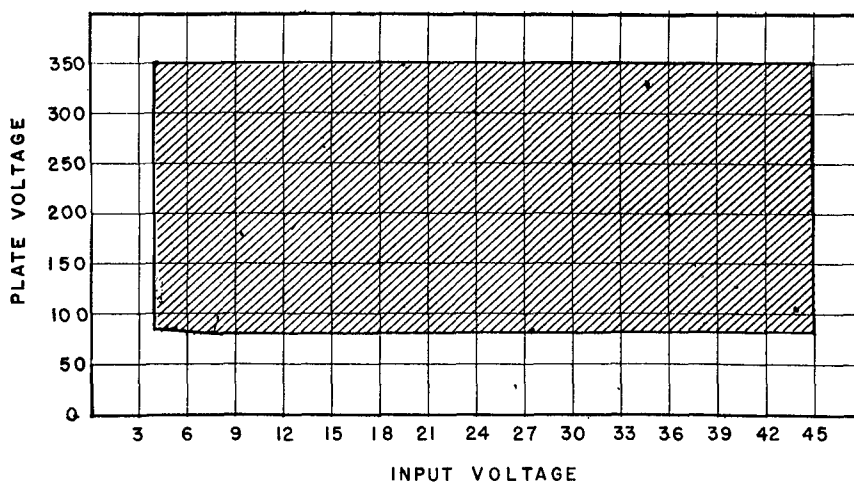


Figure 7 - Operating characteristics of the second type divider

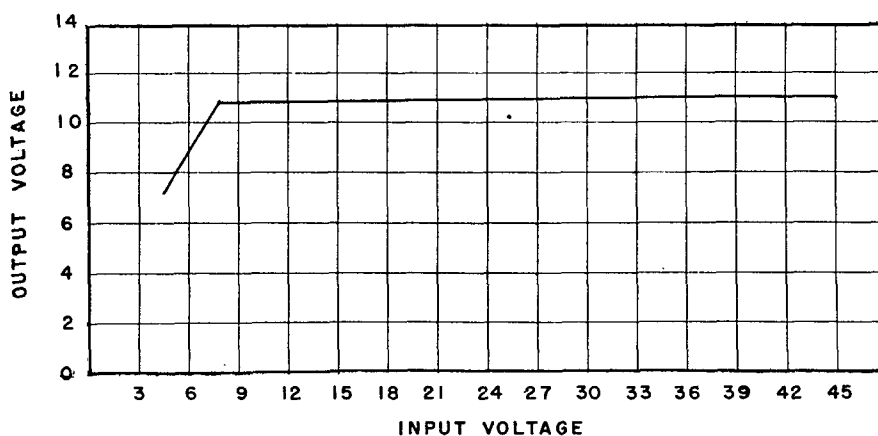


Figure 8 - Input-output voltage characteristics of the second type divider

The basic principle of operation of both dividers, Figures 4 and 5, may not appear to be different from descriptions here and in the literature, nevertheless more efficient harmonic production takes place and certain advances are realized, as follows: (1) high division ratio (10) without cascade multiplier stages, (2) completely self starting action, (3) wide permissible variation of signal voltage, (4) wide permissible variation of plate voltage, (5) the usual advantage of quasi-stable dividers, no self-oscillation and constant phase relation between f and f/N .

Both types of dividers can be conveniently contained in a space approximately 3 x 15-1/2 x 4-1/2 inches high. Figure 9 is a representative 10 kc to 1.0 kc divider built about the circuit, Figure 5.

The advantages of the circuits, Figures 4 and 5, over prior art circuits such as Figure 2, is thought to be due to the addition of the 3 kc tuned circuit in the plate of the 6SA7 mixer which augments mixing efficiency and makes the multiplier, Figure 4, multiply by 9 and 3

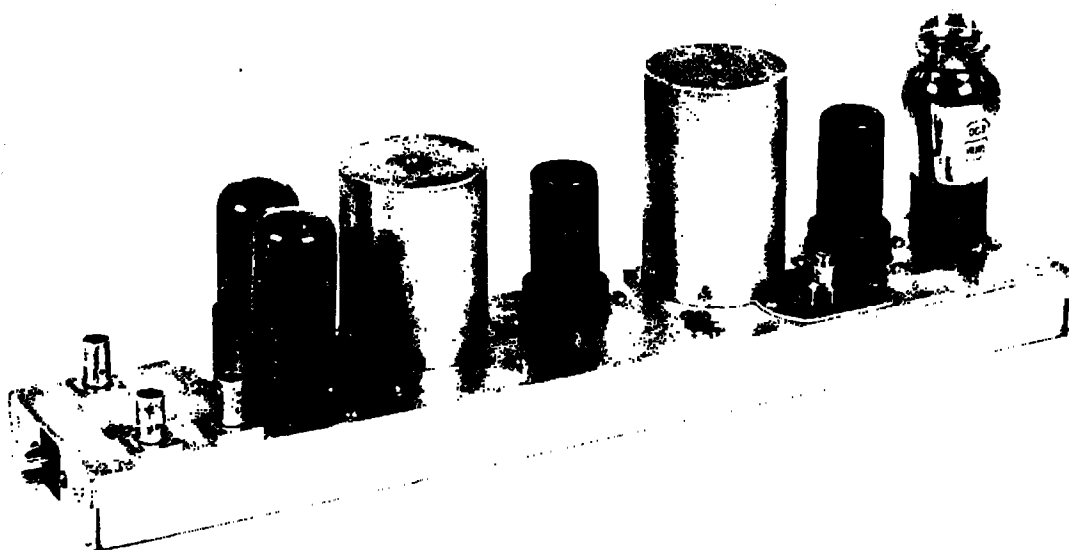


Figure 9 - Representative 10 kc to 1.0 kc divider built about the circuit of Figure 5

simultaneously. In the case of the divider of Figure 5, the process of augmented harmonic production is carried still further.

HIGH Q COILS

Probably the most important factor contributing to the improved performance of the dividers, Figures 4 and 5, is the proper construction of the inductances employed in the tuned circuits. It was determined that a necessary requirement was that the Q of the coils in the circuit be greater than 25. In order to obtain as high a Q as possible, multiple wound coils were constructed on powdered iron slugs and toroidal coils were wound on permalloy rings. The inductance of the coils was kept low so that the impedance as given by $Q\omega L$ would remain low. In this manner, resistances that shunted the tuned circuits were made to have a minimum effect.

CONCLUSIONS

The results of developmental work on the dividers shown by Figures 4 and 5 indicate that satisfactory reproducible dividers can be made for several frequency division ranges. The particular circuits have a high division ratio, require no voltage-regulated power supplies, and exhibit self-starting and locking qualities heretofore not available with regenerative frequency divider techniques. The principle of employing multiple-tuned circuits so that simultaneous multiplication can take place, and the addition of crystal rectifier distorters represent a needed contribution to the field of regenerative frequency dividers.

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